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Commercial Flight Crew Decision-Making during Low-Visibility Approach Operations using
Fused Synthetic / Enhanced Vision Systems

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Abstract

NASA is investigating revolutionary crew-vehicle interface technologies that strive to proactively overcome aircraft safety barriers that would otherwise constrain the full realization of the next-generation air transportation system. A fixed-based piloted simulation experiment was conducted to evaluate the complementary use of Synthetic and Enhanced Vision technologies. Specific focus was placed on new techniques for integration and/or fusion of Enhanced and Synthetic Vision and its impact within a two-crew flight deck on the crew's decision-making process during low-visibility approach and landing operations. Overall, the experimental data showed that significant improvements in situation awareness, without concomitant increases in workload and display clutter, could be provided by the integration and/or fusion of synthetic and enhanced vision technologies for the pilot-flying and the pilot-not-flying. During non-normal operations, the ability of the crew to handle substantial navigational errors and runway incursions were neither improved nor adversely impacted by the display concepts. The addition of Enhanced Vision may not, unto itself, provide an improvement in runway incursion detection without being specifically tailored for this application. Existing enhanced vision system procedures were effectively used in the crew decision-making process during approach and missed approach operations but having to forcibly transition from an excellent FLIR image to natural vision by 100 ft above field level was awkward for the pilot-flying.

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The United States air transportation system is undergoing a transformation to accommodate a projected 3-fold increase in air operations by 2025 (Joint Planning and Development Office, 2004). Technological and systemic changes are being developed to significantly increase the capacity, safety, efficiency, and security for this Next Generation Air Transportation System (NextGen). One of the key capabilities envisioned to achieve these goals is the concept of Equivalent Visual Operations (EVO), whereby Visual Flight Rules (VFR) operational tempos and procedures (e.g., separation assurance) are maintained independent of the actual weather conditions. One approach to attain the goal of EVO would be the creation of a virtual visual flight environment for the flight crew, independent of the actual outside weather and visibility conditions, through the application of Enhanced Vision (EV) and Synthetic Vision (SV) technologies.

NASA is investigating revolutionary crew/vehicle interface (CVI) technologies that have the potential to optimize situation awareness and reduce the propensity for, and minimize the risks associated with, pilot error while proactively overcoming aircraft safety barriers that would otherwise constrain the full realization of the NextGen (National Aeronautics and Space Administration, n.d.). Part of this research effort involves the use of EV and SV systems and other interface modalities as enabling technologies to meet the safety challenges of the NextGen EVO operational concept – that is, having the safety and capacity rates of present-day VFR operations in Instrument Meteorological Conditions (IMC).

Synthetic and Enhanced Vision

SV is a computer-generated image of the external scene topography, generated from aircraft attitude, high-precision navigation, and data of the terrain, obstacles, cultural features, and other required flight information. SV provides significant improvements in terrain awareness and reductions in the potential for Controlled-Flight-Into-Terrain incidents/accidents compared to current cockpit technologies (Kramer, Arthur, Bailey, & Prinzel, 2005; Arthur, Prinzel, Kramer, Bailey, & Parrish, 2003; Schiefele et al., 2005; Schnell, Theunissen, & Rademaker, 2005).

EV (or Enhanced Flight Vision System, EFVS) is an electronic means to provide an image of the forward external scene topography by use of an imaging sensor, such as a Forward-Looking InfraRed (FLIR) or millimeter wave radar (MMWR). EV during low-visibility approach conditions provides significant improvements in flight performance, pilot workload reduction, and decreases in the propensity for missed approaches (e.g., see Connor & Mages, 1993).

The intended use of EV and SV technology mirror each other as they both attempt to eliminate low-visibility conditions as a causal factor to civil aircraft accidents and replicate the operational benefits of clear-day flight operations, regardless of the actual outside visibility condition. The methodology by which this capability is achieved through SV or EV, however, is significantly different. While some may consider the technologies to be competing; they are, in fact, complementary (Arthur, Kramer, & Bailey, 2005).

SV, by virtue of being weather-independent and unlimited in field-of-regard, is particularly advantageous during flight phases, such as approach, which may be obscured by clouds and precipitation of which an EV sensor cannot penetrate. Recognition of terrain and

cultural features may also be improved over an EV view since the display presentation is optimized by the display designer, not the product of the sensor and its environment. Pilot recognition of EV terrain and cultural features depends upon the reflected, emitted, and / or refracted energy at the spectral frequencies of the EV sensor and the ability of the pilot to (correctly) interpret this image. Atmospheric effects, time of day, and sensor characteristics can be important factors in the quality of the EV imagery. On the other hand, EV provides a direct view of the vehicle external environment; independent of the derived aircraft navigation solution or of a database. Under conditions of smoke, haze, and night, a FLIR/EV provides orders-of-magnitude improvement over the pilot's natural vision; greatly enhancing the pilot's situation awareness and reducing the pilot's workload. The comparison of SV and EV, as shown in Figure 1, on a night visual meteorological conditions (VMC) approach into an airfield highlights the similarities and differences in these two technologies.

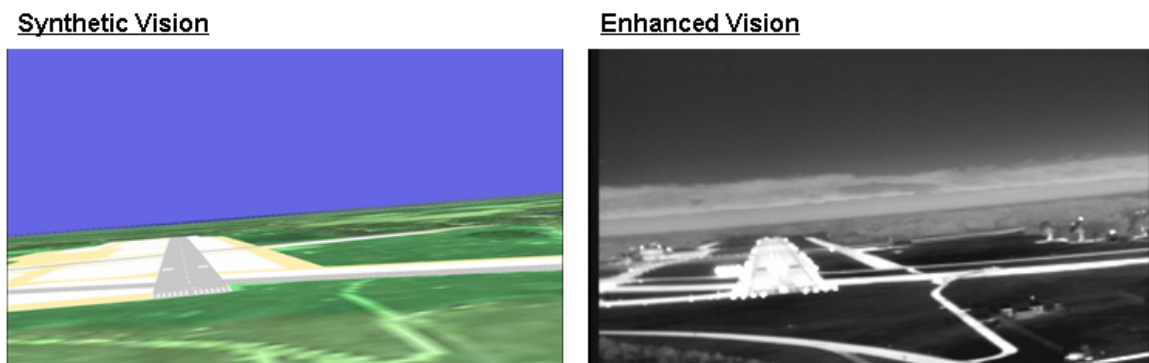


Figure 1. Synthetic vision and enhanced vision comparison.

Past Research

Previous synthetic vision research (Parrish, Busquets, Williams, & Nold, 2003) has shown that a “flight-critical” synthetic vision implementation which uses automated decision aiding functions for object detection and database alignment/navigation error detection produces superior performance to synthetic vision concepts with an EV inset display. To date, however,

technology for “perfect” object detection and database/navigation error detection does *not* exist. Further, even if these systems come to fruition, there may still be gaps, such as minimal radar cross section objects or below-threshold detection values, which may require other additional integrity and error checks.

SV with EV inset displays *may* offer one possible method to provide the pilot with information sufficient to perform navigation integrity and obstacle clearance checks. While these concepts are viable, performance and pilot workload (Parrish et al., 2003) suffer in comparison to automated methods to achieve these same capabilities. Other studies have shown similar results (McKay, Guirguis, Zhang, & Newman, 2002). Object detection by pilots was found to be best using a dedicated EV display, as opposed to a “shared” display, particularly one that did not include symbology. (However, the presence or absence of symbology was not tested.) From this study and others, the ability of pilots to perform navigation integrity checks and obstacle identification principally depends upon the visual acuity provided by the displayed imagery for the pilot (Boff & Lincoln, 1988), as affected by the resolution and acuity of the sensor and display systems; the characteristics of the object and its surrounding scene or background features; the display clutter; display size; and the display and object color and contrast characteristics.

While EV might improve SV operations, the converse warrants investigation as well. In 2004, Section 91.175 of the Federal Aviation Regulations was amended such that operators conducting straight-in instrument approach procedures (other than Category II or Category III) may now operate below the published Decision Height (DH) and Minimum Descent Altitude (MDA) when using an approved EFVS on the pilot’s Head-Up Display (HUD). This rule change now provides “operational credit” for EV. As such, EV operations will become more prevalent.

No such credit currently exists for SV. However, SV may be advantageous during flight phases, such as approach, in aiding the pilot's awareness of terrain, obstacles, and flight path which may be obscured by clouds and precipitation of which an EV sensor cannot penetrate. SV may also provide the crew with "visual momentum" to assist the crew's understanding and correct interpretation of the EV sensor imagery.

Current Study

A fixed-based simulator experiment was conducted to evaluate the complementary use of SV and EV technologies, specifically focusing on new techniques for integration and/or fusion of synthetic and enhanced vision technologies and its influence on crew coordination during low-visibility approach and landing. The objective of this experiment was to test the utility, acceptability, and usability of integrated/fused EV and SV technology concepts in a two-crew commercial or business aircraft cockpit; these results are described in Bailey, Kramer, and Prinzel (2006). The current paper describes experimental results specific to crew decision-making during low-visibility approach and crew response to non-normal events that were staged in this experiment using a fused synthetic/enhanced vision system.

Method

Subjects

Twenty-four pilots, representing seven airlines and a major cargo carrier, participated in the experiment. All subjects had previous experience flying with HUDs. The subjects had an average of 1787 hours of HUD flying experience and an average of 13.8 years and 16.2 years of commercial and military flying experience, respectively. EV experience was not required although some pilots were familiar with imaging sensor technology from prior military flight experience. None of the subjects were flying EV in current operations.

Simulator

The experiment was conducted in the Integration Flight Deck (IFD) simulation facility at NASA Langley Research Center (LaRC). The IFD emulates a Boeing B-757-200 aircraft and provides a full-mission simulator capability. The collimated out-the-window (OTW) scene is produced by an Evans and Sutherland ESIG 4530 graphics system providing approximately 200 degrees horizontal by 40 degrees vertical field-of-view (FOV) at 26 pixels per degree resolution. The OTW imagery used the same source data as the SV database. The subjects occupied the left (as pilot-flying, PF) and right (as pilot-not-flying, PNF) seats. The left seat included an overhead HUD projection unit and the right seat included an auxiliary display (AD) under the right side window. Traditional primary flight and navigation displays were presented head-down.

Head-Up Display

The HUD subtended approximately 32° horizontal by 24° vertical FOV. The HUD presentation was written strictly in a raster format from a video source (RS-343) input. The input consisted of a video mix of symbology and computer-generated scene imagery (either EV or SV as described in the following). The symbology included “haloing” to ensure high-contrast symbology against the scene imagery background. Brightness and contrast controls were provided to the pilot. Also, the pilot had a declutter control, implemented as a push-button on the left hand horn of the PF yoke. The button cycled through three “declutter” states: 1) No declutter (full symbology and scene imagery); 2) “Raster” declutter (full symbology, no scene imagery); and 3) “Full declutter” (no HUD display).

Four HUD display concepts (see Figure 2) were tested, differing from each other in: 1) the type of raster background presented; and, 2) in the type of symbology presented. Two raster formats were flown, either EV only (hereinafter referred to as “FLIR”) or a fusion SV/EV image

(hereinafter referred to as “Fusion.”) The FLIR HUD concept represented our “baseline” EFVS HUD condition. In this configuration, the simulated FLIR output was exclusively displayed whether useful imagery of the external scene topography was being provided or not. The Fusion HUD concept represents one method of providing complementary SV/EV information for the pilot flying. The Fusion raster started out as unadulterated SV imagery, transitioning through a fused SV/EV presentation beginning at 600 ft (183 m) above field level (AFL), and ending with unadulterated FLIR imagery by 500 ft (152 m) AFL. Between 600 feet and 500 feet AFL, a step function modulated the fusion from 100% SV/0% EV ending at 0% SV/100% EV.

Each raster concept showed FLIR-only below 500 ft to take advantage of the operational credit now offered by use of FLIR on the HUD. The 500 ft transition altitude was chosen from a usability study prior to the test and flight experience (Kramer, Arthur, et al., 2005) balancing the following factors: 1) FLIR imagery is required no lower than 200 ft (61 m) AFL to provide an operational credit for FLIR usage, yet there is sufficient time (from 500 ft to 200 ft) to become acclimated to the FLIR imagery, 2) SV imagery for the Fusion concept can assist the PF in establishing and maintaining stabilized approach parameters (the minimum recommended IMC stabilized approach altitude is 1000 ft (305 m) AFL); and, 3) 500 ft AFL is at or just after the recommended minimum VMC stabilized approach altitude to allow full utilization of EV. The 100 ft (30.5 m) transition between SV and EV for the Fusion concept imparts visual momentum between the different image sources for the PF HUD.

The two raster formats (FLIR, Fusion) were factorially combined with two symbology sets: (1) The standard HUD symbology (hereafter referred to as “Baseline”) and (2) the same standard HUD symbology enhanced with pathway guidance and a runway outline (hereafter referred to as the “Tunnel” symbology set). The “tunnel” symbology set (Kramer, Prinzel,

Arthur, & Bailey, 2005) was tailored to transition at the same altitude of 500 ft AFL as the Fusion raster. The tunnel ended at 500 ft AFL to minimize clutter and was replaced by the glideslope reference line to ensure approach path angle awareness. Below 500 ft, the only additional symbology in the Tunnel symbology set, over and above that of the Baseline set, was the runway outline symbol. (Note that below 500 ft, the FLIR-Baseline and Fusion-Baseline configurations were identical.)

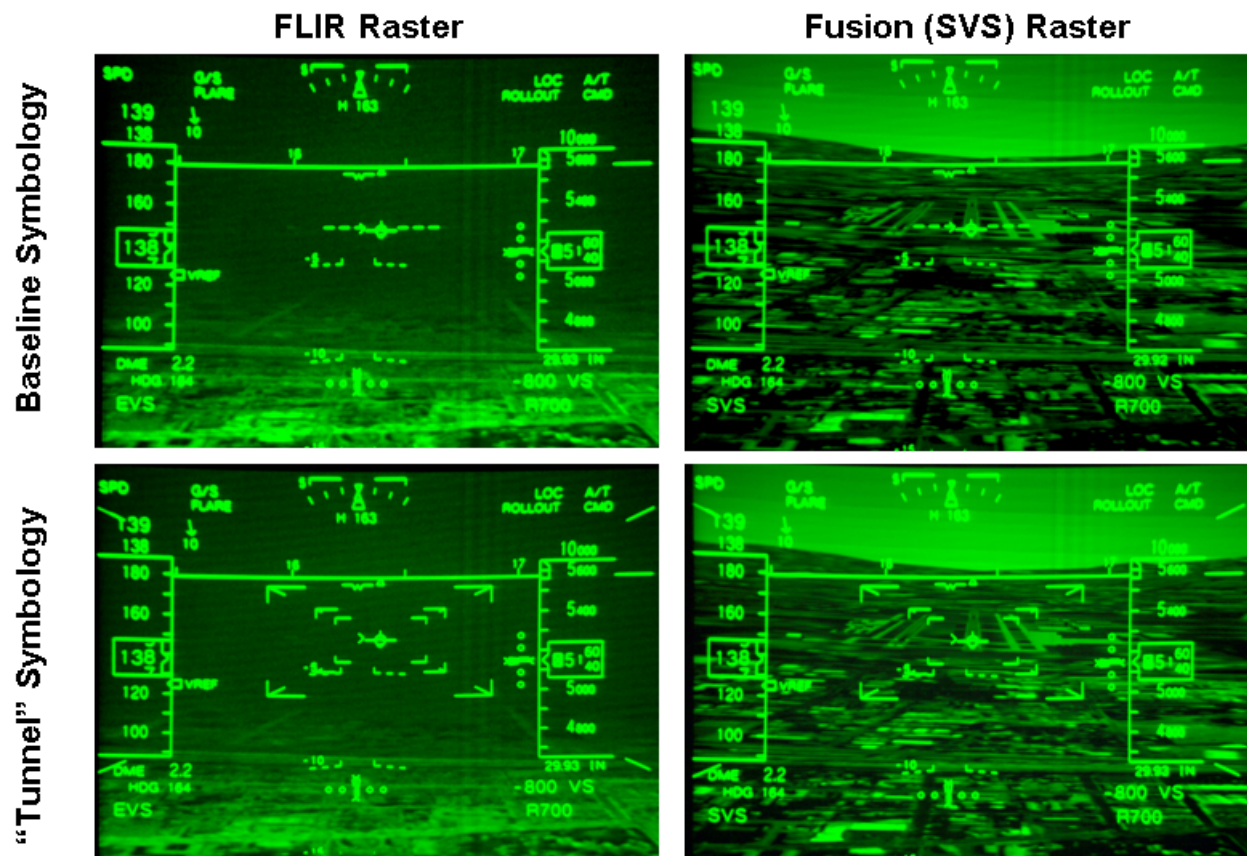


Figure 2. Head-Up Display (HUD) formats on approach at 700 feet AGL

In Figure 2, all four PF-HUD concepts are shown - the FLIR-Baseline, FLIR-Tunnel, Fusion-Baseline, and the Fusion-Tunnel. In the FLIR-Baseline concept, a minimum of symbology is used and the FLIR does not necessarily provide terrain and runway cues. (The FLIR imagery depends, for instance, upon the simulated atmospheric conditions.) Conversely, the Fusion-Tunnel concept uses tunnel guidance for distinct path demarcation and SV for clear

terrain and runway references, above 500 ft AFL. Below 500 ft with the Tunnel symbol set, the runway outline provides an element of SV, creating “visual momentum” within the EV raster background image and also, a direct indication of the navigation solution accuracy if the runway is visible in the FLIR imagery.

Auxiliary Display

The PNF-Auxiliary Display (PNF-AD) was located outboard of the PNF location. The display was positioned as a compromise between optimal PNF viewing position, minimal display/instrument panel obscuration, and moderate installation complexity. The 8.4 in (21 cm) diagonal display was full-color with 1024 x 768 pixel resolution. The display video source was a video mix of “haloed” symbology and computer-generated scene imagery (either EV or the output of a fused EV/SV signal as described below).

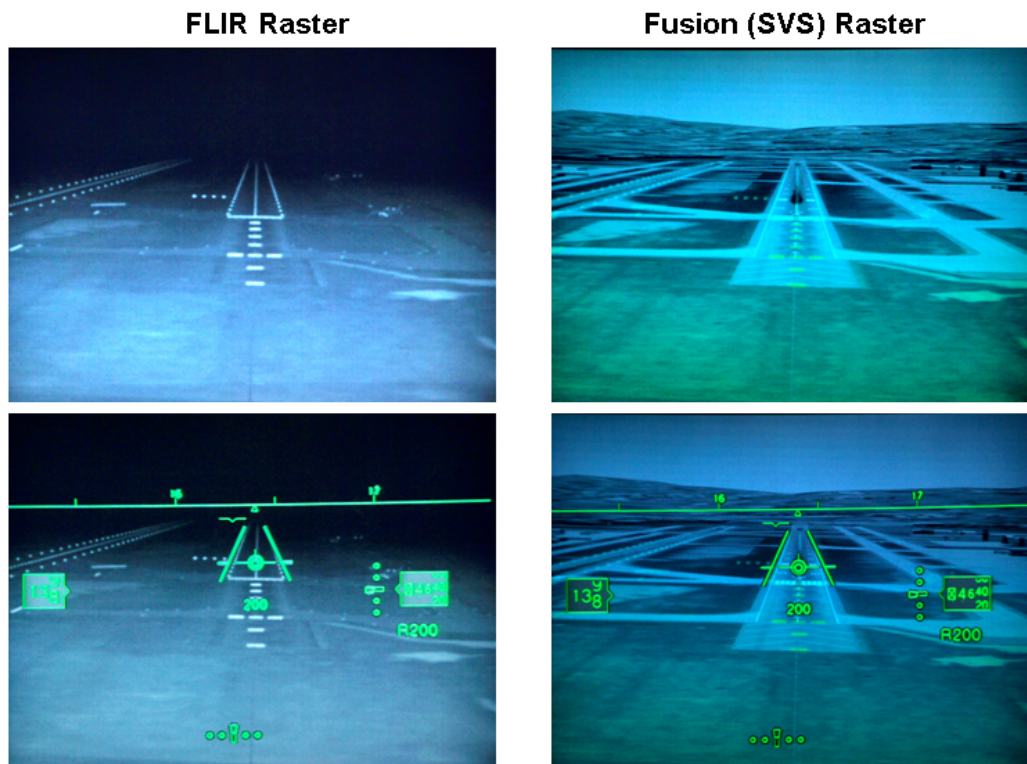


Figure 3. Four Auxiliary Display (AD) formats on final.

Four PNF-AD display concepts (see Figure 3) were tested, differing from each other in: 1) the type of raster background presented; and, 2) the type of symbology presented. The raster was either EV only (hereinafter referred to as “FLIR”) or a fused SV/EV image (hereinafter referred to as “Fused”). The symbology was either “On” or “Off” for the data runs. When present, the symbology was a subset of the standard HUD symbology (see Figures 3).

The AD-fused raster image was pilot-controllable and could be controlled throughout the approach to one of 10 states: FLIR only, SV only, or 8 fusion combinations of FLIR and SV, using an Equinox EP-3000™ fusion board. The fusion employs a feature-level extraction algorithm with two pilot control inputs: (1) feature-level fusion of FLIR and SV and (2) modulation of false-color coding of the fusion image.

In Figure 3, examples of the four PNF-AD concepts are shown: FLIR-No Symbology (upper left), FLIR-Symbology (lower left), Fused-No Symbology (upper right), and Fused-Symbology (lower right).

Evaluation Task

The evaluation task was selected to approximate what may be typical of the emerging NextGen concept called an “equivalent visual operation.” The task was based on a published visual arrival – reflecting an efficient and preferred routing for Air Traffic Control (ATC) and noise-abatement – which currently requires VMC for the pilot to see-and-avoid terrain, traffic, and obstacles while navigating with respect to ground references. The approach path is not too dissimilar from a Required Navigation Performance (RNP)-type arrival, requiring a curved, descending path. The evaluation task tests the ability of SV and EV technologies to support this type of operation by providing “equivalent visual” information into the cockpit. Further, if this technology succeeds in providing a visual arrival capability, the potential for operational

efficiency and minimums reduction above and beyond what can be provided by RNP may be offered.

The PF hand-flew the base and final leg portions of the Sparks Visual Arrival to RNO (FAA identifier for Reno/Tahoe International Airport) Runway 16R (16 Right) with autothrottles engaged at an approach speed of 138 knots. The Sparks Visual Arrival requires VFR conditions under today's operating rules. However, to test the efficacy of the concepts for EVO capability, visibility was reduced significantly to IMC. The aircraft was configured for landing prior to each run (landing gear down and flaps 30 degrees). The path converged into the Instrument Landing System (ILS) for Runway 16R. The aircraft was configured to land and, if properly flown, the aircraft would be on the ILS and on a stabilized approach by 1000 ft (305 m) AFL. The PNF monitored the approach from the right-hand side of the flight deck using standard instruments and the AD. Subjects were instructed that the run would end at main gear touchdown but that they should perform a go-around if they felt the landing was not safe.

Enhanced Vision System Crew Procedures

To aid crew decision-making during low-visibility approach operations, enhanced vision system (EVS) crew procedures (adapted from those currently used in business aircraft EVS operations) were established. Instructions in the use of the procedures were given to each crew. An overview of these procedures is given in Table 1, including automatic call-outs. The altitude call-outs were set-up assuming a 200 ft DH for the published, non-EVS approach. (A "flat-earth" model was simulated so differences between the barometric altitudes and radar altitudes for decision altitudes/heights were inconsequential.)

Table 1

EVS Crew Procedures

| Altitude-Based Events | AFL / Barometric-Altitudes (ft) | Automatic Callouts | Pilot Flying (PF) Tasks | Pilot Not Flying (PNF) Tasks |
|-------------------------------------|---------------------------------|-------------------------------|---|--|
| 500 feet AFL | 500 / 4912 | “500” | Response: <i>“Systems Normal, EVS Normal”</i> | Call <i>“500 feet”</i> |
| 100 feet Above Minimums | 300 / 4712 | “Approaching Minimums” | Response: <i>“Check”</i> | Call <i>“100 feet Above”</i> |
| Published Minimums (200 ft AFL) | 200 / 4612 | “Minimums” | With <u>EVS Visual Cues</u>, Call “EVS Lights” | When <u>Visual Cues</u> Appear Call “Lights” or “Field in Sight” |
| | | | Without <u>EVS Visual Cues</u>, Call “Going Around” | Without PF Call of ‘EVS Lights’, Call “Go Around” |
| EFVS Decision Altitude (100 ft AFL) | 100 / 4512 | | When <u>Actual Visual Cues</u>, Call “Landing” | When <u>Visual Cues</u> Appear, Call “Lights” or “Field in Sight” |
| | | | Without <u>Actual Visual Cues</u>, Call “Going Around” | Without PF Call of ‘Landing’, Call “Go Around” |

At 500 ft AFL, the “EVS Normal, System Normal” call by the PF corresponds to the point where the PF would nominally check that the EVS was set-up properly and functioning properly on the approach. In our test, this call-out cued the PF to ensure that the HUD declutter, brightness and contrast were properly set. No EVS controls were available to the flight crew in the experiment. The EPs were instructed that the FLIR was always set to its optimal sensor setting for the approach and landing.

By the established decision height of 200 ft (AFL), the crew procedures dictate that the PF must have the required EFVS references or the required landing visual references (using natural vision) to continue the descent. The landing references were those published in FAR §91.175. For this test, the approach light system for RNO 16R provided the prominent EFVS references. If these EFVS references were visible, the PF was instructed to call “EVS Lights”. If the PF saw the lights or markings of the threshold (the predominant landing visual reference

for RNO 16R), the PF called “Landing.” The “landing” call was required no later than 100 ft AFL.

The PNF provided monitoring, including back-up on all decision heights, and was instructed to call “go-around” if “EVS Lights” was not called at or before 200 ft DH or if “Landing” was not called by 100 ft DH. The PNF was allowed to assist the PF in picking up the required visual cues (normal or EFVS). Transfer of control between the Captain and First-Officer was not permitted.

The crew procedures were new to all of the flight crews. Some procedures were counter to, others consistent with, their current airline Standard Operating Procedures (SOPs). In either case, the crew procedures were trained and “enforced” for the test as specific guidance on crew tasks and expected crew responses to assist decision-making for EVS-approach and landing operations. During the post-test debrief, questions and issues of how these procedures may or may not work within their airline operation and SOPs were discussed. Flight crews from the same airline were paired to the greatest extent possible to minimize SOP differences and to mitigate potential interference in crew interaction.

Experiment Matrix

Nominally, forty experimental runs were completed by the evaluation crew with each pilot flying 20 approaches evaluating the HUD concepts and with each pilot monitoring 20 approaches while evaluating the AD concepts.

The wind and weather varied on each run. The nominal visibility in the EVS and OTW varied from 1 mile down to 0.5 mile (1.6 to 0.8 km). The required EVS visual references became visible on the HUD between 450 ft (137 m) and 250 ft (76 m) AFL. Four runs per flight crew were specifically designed so the EVS visual references were visible but the required

runway (normal vision landing) references were not. With good crew decision-making and in accordance with the proper use of the EVS crew procedures, these four runs should conclude by a go-around initiated no lower than 100 ft AFL.

The PF was instructed to fly each approach as precisely as possible using the display information available, as the effect of the display information on the PF's ability to fly the approaches would be quantitatively and qualitatively evaluated. In addition, the PF was instructed to land as close as possible to the centerline of the runway.

Rare Event Testing

A significant component of the test, in addition to the nominal runs, was met by measuring the ability of the flight crew to react and properly handle non-normal events. Four non-normal runs were flown by each crew. The non-normals were runway incursion (RI) scenarios and database integrity monitoring scenarios. The number and ordering of RI and database integrity scenarios were designed to avoid expectancy on the part of the flight crew (Foyle & Hooey, 2003).

The RI scenarios simulated an incursion with either a non-transponding baggage cart or fire truck. Both vehicles were stationary and positioned in the same location, approximately 850 ft (260 m) from the RNO Runway 16R landing threshold and just slightly offset from the centerline. They were both positioned perpendicular to the runway (i.e., they were facing toward the runway edgelines.) The weather on the runway incursions was held constant at 2400 ft (732 m) runway visual range (RVR) OTW with the lowest cloud layer at 500 ft (152 m) AFL. The FLIR visibility was very good in this condition – approximately 4 times the OTW RVR. The baggage cart runway incursion was always performed before the fire truck incursion. The

baggage cart was much more difficult to see due to its small size. This ordering tested for “just noticeable differences” for runway incursion detection.

The database integrity monitoring scenarios purposefully introduced a lateral navigation solution error (of either 50 or 75 feet { 15 or 23 m}) with respect to the real runway. This error resulted in the synthetic vision terrain, pathway and guidance cue being misaligned from the FLIR and ILS data (which were defined in the flight crew briefing as being correct).

Procedure

The subjects were given a 1-hour briefing to explain the SV/EV concepts on the HUD and AD, EVS crew procedures, and the expected evaluation tasks. After the briefing, a 2-hour training session in the IFD was conducted to familiarize the subjects with the aircraft handling qualities, display symbologies, EVS crew procedures, and controls. The ‘rare-event’ scenarios were not discussed, although the pilot’s responsibility for maintaining safe operations at all times was stressed. Data collection lasted approximately 4.5 hours followed by a 30-minute semi-structured interview. The pilots were also given a take-home final questionnaire. The entire session including lunch and breaks lasted approximately 9 hours.

Results

The focus of this journal article is on the crew decision-making process on approach while evaluating integrated/fused enhanced and synthetic vision technologies and on the crew’s reaction to non-normal flight situations (navigation errors and runway incursions). A thorough discussion of the pilots’ path control performance (lateral and vertical) and pilot ratings of mental workload, situation awareness, display clutter, and display preferences are detailed in Bailey, et al. (2006). Overall, the experimental data showed that significant improvements in pilot situation awareness (SA), without concomitant increases in workload and display clutter,

could be provided by the integration and/or fusion of synthetic and enhanced vision technologies for the PF and the PNF. Similarly, SA improvements without workload or display clutter penalties were found by the addition of the tunnel with the HUD imagery for the PF and by the addition of fusion control and symbology on the AD for the PNF.

Illegal Landings and Their Effect on Crew Decision-Making

To test crew-decision making on approach, each flight crew was confronted with four trials where weather conditions obscured the required visual cues necessary to complete the landing as defined by FAR §91.175. Of the 48 “illegal landing” trials, during only six of these trials did pilots continue and land the aircraft. These data are tabulated in Table 2, identifying the crew, the display concept being flown, and what the flight crew were observed doing, as opposed to initiating a go-around.

Table 2

Illegal Landing Trials

| Crew | Observation | PF-HUD Concept | PNF-AD Concept |
|------|---------------------------------------|----------------|--------------------|
| 3 | Go-around considered | FLIR/No Tunnel | Fused/No Symbology |
| 4 | Threshold lights called at 80 ft AFL | FLIR/No Tunnel | FLIR/Symbology |
| 4 | Threshold lights called at 60 ft AFL | FLIR/No Tunnel | Fused/ Symbology |
| 7 | Threshold lights called at 100 ft AFL | FLIR/Tunnel | Fused/ Symbology |
| 8 | Threshold lights called at 120 ft AFL | FLIR/No Tunnel | Fused/No Symbology |
| 11 | Threshold lights called at 90 ft AFL | FLIR/No Tunnel | FLIR/No Symbology |

The results demonstrated a small but definite potential (12.5%) for flight crews to continue approaches to a landing during visibility conditions that instead require a go-around under the §91.175 operational rules for EFVS. On all of the illegal landing scenarios, the pilot flying had excellent visibility of the runway using the FLIR on the HUD, but wouldn’t have been

able to see the runway visual landing references until descending below 100 ft AFL. When “threshold lights” were called by the EPs above 80 ft AFL, this observation was either erroneous (i.e., they could *not* in fact see the threshold lights using natural vision) or they saw the threshold lights in the EFVS image itself and were confused about which was EFVS and which was natural vision. (The current §91.175 EFVS rule requires visual acquisition of the runway references *without* use of the EFVS by 100 ft height above touchdown, or HAT.)

No statistically significant effects of symbology type on the HUD concept was observed, although 5 of the 6 events occurred when the runway outline was not present.

The operational procedures necessary to follow the §91.175 regulation (i.e., for seeing the runway with “un-aided” vision by 100 ft HAT) were generally found to be awkward for the PF. The brightness on the HUD was selected by each PF for good readability, yet dim enough to promote viewability of the outside scene. However, the brightness of the Out-the-Window (OTW) visual scene was typically not sufficient to “burn-through” the imagery shown on the HUD, requiring the PF to declutter the HUD or to look-around the HUD combiner. (The brightness of the OTW was obviously not equivalent to real-world flight conditions, but “burn-through” of real-world imagery, while more likely in actual flight conditions, cannot be guaranteed.) The flight crew understood the rationale for the natural vision acquisition of the landing references, but the fact that the pilot flying had excellent visibility of the runway using the FLIR made it very tempting to continue the approach to landing despite the rule.

Adherence to the minimums was also hindered by crew duties. The radio altitude shown on the HUD could be used for judging HAT, but the PF was concentrating primarily on lateral line-up and flare, focusing on the flight path marker and the image of the runway in the FLIR – not the displayed radar altimeter readout. The PNF was typically “eyes-out” and not closely

monitoring the altitude (shown on the head-down displays) below 200 ft AFL (Bailey, Kramer, & Prinzel, 2007). An aural call-out of 100 ft may have aided adherence to the DH. The aural call-outs were set to Cat. I decision heights (i.e., the aural call-out of “Minimums” occurs at 200 ft AFL.).

The few occurrences of “below minimums” landings suggest that the current regulations can be operationally viable. However, to further aid crew decision-making, an aural call-out at 100 ft AFL is recommended. Nonetheless, the PF’s required transition from EV/HUD-to-visual runway references was awkward. The PFs typically commented that the EFVS provided suitable visual references to complete the flare and landing.

Non-Normals

Non-normals were injected into the test without the evaluation subjects having prior knowledge of them. The non-normals were two runway incursions and four lateral offset navigation errors for each flight crew.

Runway Incursions

The runway incursions were created by a baggage cart and a fire truck. While many issues factor into the data analysis for runway incursion, four of the key attributes that must be considered in analyzing these data are: display resolution, target size, display color (presence and absence), and the presence or absence of symbology. These factors will be discussed in relation to the experimental data.

To put the RI results into perspective of display resolution, the EVS and OTW (simulated) visual scene resolutions were used to compute the altitude AFL that the RIs *might* be reasonably expected to be observed by the crew. While target detection is critically dependent upon visibility, lighting, target contrast, color, gray scales, etc., resolution is only used in this

example. In this example, it is assumed that 10 pixels (scan lines) are required for a human observer to recognize a target/object in this example (Larimer, Pavel, Ahumada, & Sweet, 1992). The baggage cart consisted of a tug and a cart. The tug was approximately 7.5 ft (2.3 m) tall and 10 ft (3 m) long, tied to a cart 6.5 ft (2 m) tall and 10 ft (3 m) long. The Fire Truck was 31.6 ft (9.6 m) long and 13 ft (4 m) tall. An operating rotating beacon was depicted atop the Fire Truck.

In Table 3, the height of the aircraft (AFL) when 10 lines (pixels) draw the incurring vehicles is shown. The analysis assumes a 3 degree glideslope and the limiting resolution of the EVS shown on the HUD and PNF-AD was the simulated FLIR (640x480 resolution). The HUD and PNF-AD EVS resolution was 20 pixels per degree. The OTW resolution provides 26 pixels per degree. The vertical and horizontal resolutions were identical.

Table 3

Above Field Level (AFL) Altitudes for Theoretical Detection of Runway Incursions

| Object | Dimension / Scan Direction | AFL Altitudes for EVS "Detection" | AFL Altitude for OTW "Detection" |
|---------------------|----------------------------|-----------------------------------|----------------------------------|
| Baggage Cart | Height | 42 ft | 58 ft |
| | Width | 120 ft | 156 ft |
| Fire Truck | Height | 78 ft | 101 ft |
| | Width | 190 ft | 246 ft |

The theoretical detection ranges show that the Fire Truck should be detectable at almost twice the distance as the Baggage Cart, particularly its vertical extent (i.e., height). The OTW provided better detection capability because of its higher resolution (a 30% improvement). Finally, none of the vehicles were theoretically "detectable" in this analysis above 200 ft AFL using the EVS (i.e., using the HUD or PNF-AD). It should be noted, however, that the Fire Truck was visually detectable above 200 ft AFL using the EVS, *if* the observer was cued to its existence and studied the display.

The experimental results showed that, for the 12 flight crews, only one crew member (PNF) saw the baggage cart (they saw it in the OTW) and initiated a go-around. The other 11 crews had a runway incursion with the baggage cart. From the analysis of Table 3, the baggage cart should be “detectable” between 50 and 150 ft AFL but this leaves only 5 to 15 seconds before landing – not very much time to spot a small object, parked slightly short of the intended touchdown zone.

Eleven crews saw the Fire Truck OTW (7 by the PNF, 3 by the PF, and 1 simultaneously by the PF and PNF) and the one remaining crew saw it on the PNF-AD. Upon seeing the incursions, all crews initiated a go-around (all lower than 50 ft AFL).

The incurring vehicles were visible in the PNF-AD and HUD, yet the data suggests that EV on the HUD and PNF-AD were not useful for RI detection. Only one of the runway incursion scenarios was detected through use of the EVS imagery on the cockpit displays. These data highlight several important factors in RI detection by flight crews:

- the vehicles were stationary so motion effects which might aid target detection were absent.
- the incurring vehicle scenarios were low luminance and low color contrast targets. Acuity metrics, such as those used in the example in Table 3, will provide optimistic detection performance since the metrics typically assume relatively high contrast targets. Whatever color contrast was available between the incurring vehicles and the runway background was only available to the pilots when using the OTW information for detection – not in the monochromatic EVS.
- the flight path marker and guidance cue symbology on HUD or on the PNF-AD (when used) largely occluded the incurring vehicles as they were positioned near

the touchdown aimpoint. The flight path marker shows precisely where the aircraft is going, but it will also obscure raster background imagery, thus, hiding a potential runway collision.

- the experimental HUD, like all HUDs currently manufactured, has limited contrast (gray scale) ranges. Object detection is much more likely when using the PNF-AD than the HUD because of its significantly higher gray scale range.

Further, the HUD image contrast was also a function of pilot control.

Pilot duties are another important consideration on RI detection and in interpreting these experimental data. The PF was consumed with the task of flying the aircraft and identifying the proper visual references for landing. Therefore, successful runway incursion detection at this late stage on the approach by the PF should not be considered as a likely outcome. The data confirmed this hypothesis in that the PF detected only 4 out of the 24 runway incursions.

On the other hand, the PNF was tasked with monitoring the flight. Using the PNF-AD, the vehicles were much more apparent than in the HUD, but the data does not indicate significantly greater detection success using this display. The PNF-AD display is more attuned to the RI detection task because of the lack of symbology (in some cases) and its improved gray scale contrast performance. But, as the theoretical detection example showed (Table 3), the vehicle size and EVS resolution make detection on the PNF-AD moderately difficult above 200 ft AFL. Below 200 ft AFL, the vehicles were much more obvious in the image, but the PNFs noted that they were head-out the vast majority of the time. PNF head tracking measurements collected in this experiment (Bailey, et al., 2007) quantify this pilot comment. The PNF was head-out the vast majority of the time, ranging from 86% to 100% of the total time below 200 ft. AFL. Based on these data and the pilot comments, the use of the PNF-AD for incursion

detection was not probable. The presence of symbology on the PNF-AD could also have obscured the vehicles, particularly if the PNF only used cursory looks at the PNF-AD. It appears that the use of PNF Fusion controls when available (i.e., toggling between SV and EV imagery) did not statistically help or hinder detection (Bailey, et al., 2007).

Unlike the PF, the PNF is tasked with monitoring the approach and the landing area. 9 out of 24 incursions were detected by the PNF. But, starting around 500 ft AFL and below, the PNF is going “eyes-out” so runway incursion detection using a head-down display may not be practical (only one PNF saw the incursion in the AD). The off-boresight design of the tested PNF-AD was noted by the pilots as hampering their use of the display on final. Current flight crews are not familiar with using head-down displays on short final to check for incursions. This was not part of the pre-experiment flight crew instructional briefing.

The results suggest that EV on the HUD and PNF-AD were not useful for RI detection. Requirements for display and sensor technology for runway incursion detection should be developed and they should span the breadth of the problem, including human perception, sensor design and detection theory, crew procedures, and crew interface issues. Current flight crews are not familiar with using head-down displays on short final to check for incursions. The displays are not necessarily optimized for this role. For instance, the capability to provide EV image “zoom” - to increase the EV resolution for object detection before the final phase of the approach – should be considered as it could increase the probability for object detection and recognition before the PNF goes “eyes-out.”

Navigation Error

The navigation errors were either a 50 ft or 75 ft (15 m or 23 m) lateral offset (see Figure 4) and could be detected by either the PF or the PNF. The errors were noticeable from one of

several principal ways (depending upon the display configuration) using various indicators: 1) by a disagreement between the lateral path error and the localizer deviation symbology (HUD and PNF-AD concepts with symbology); 2) by a non-zero localizer deviation on the primary flight display (PFD) when the PF is flying on the final approach path centerline; 3) by differences between the SV and the EV registration using the PNF-AD Fusion controls; 4) by differences between the runway outline and the EV imagery of the runway (HUD and PNF-AD concepts with symbology); or 5) by differences in the pitch/roll guidance symbol and the EV imagery (PF-HUD and PNF-AD concepts with symbology).

a) 50 ft Lateral offset as seen on PF-HUD



b) 75 ft Lateral offset as seen on PNF-AD

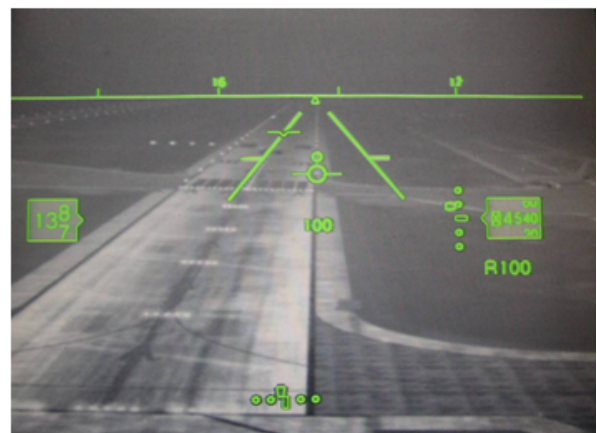


Figure 4. Lateral navigation offset examples.

The majority of flight crews verbally noted the presence of the 50 ft (15 m) offset (15 of 24 crews) and 75 ft (23 m) offset (19 of 24 crews) during the approach. None of the pilots executed a go-around with this anomaly. Each performed a lateral correction and landed near the runway centerline.

Video analysis showed that navigation errors were predominately noted by the PF (~85%) when they noticed that the pitch/roll guidance symbol was leading them to the left or right of the runway. The “real” runway was detectable in the EV image. One person (flying as

the PNF) noted the non-zero localizer deviation on the PFD presentation while tracking the path centerline.

The flight crews were not instructed on the course of action to take when confronted with a navigation error, and the pilots had relatively little training and experience with the system. Despite this, the study showed that lateral navigation errors were verbally acknowledged a significant percentage of time, and even when unrecognized (i.e., not explicitly verbalized), all flight crews landed safely and accurately on the runway. These results suggest that dissociations between raw data, sensor, and/or database presentation should be easily recognized and managed by experienced pilots. Pilot training to recognize these discrepancies should further improve operations in the event of this anomaly.

Conclusions

An experiment was conducted to evaluate the complementary use of synthetic vision and enhanced vision technologies, specifically evaluating the utility, acceptability, and usability of integrated/fused enhanced and synthetic vision technologies and its effect on two-crew decision-making during low-visibility approach and landing operations. Pilots were asked to fly RNP-type approaches under conditions of restricted visibility to evaluate the efficacy of synthetic and enhanced vision concepts for future equivalent visual NextGen operations. The research further evaluated the effect of these technologies on flight crew responses to variable weather conditions and selected rare events that may impact aviation safety during such operations. Kramer, Bailey, and Prinzel (2007) present nominal results and discuss the potential of these technologies for supporting future national airspace system operations. The current paper describes the off-nominal results on flight crew responses to below minimum landing conditions (i.e., “illegal landings”) and pilot reactions to runway incursions and navigational offset error “rare events.”

Illegal Landings

The few occurrences of “below minimums” landings suggest that the current Federal Aviation Regulation (FAR) §91.175 rules can be operationally viable with these displays. However, to further aid crew decision-making, an aural call-out at 100 ft above field level is recommended. The §91.175 regulation requires that the pilot-flying (PF) see the required vision landing references with natural vision by 100 ft Height Above Touchdown. This natural vision (versus enhanced vision) requirement caused an awkwardness for the PF in the late stages of the approach because it required the PF to declutter the head-up display (HUD) or to look-around the HUD combiner. The procedural requirement added a workload cost to the use of the EVS and added to the temporal demands imposed on the flight crew during final approach. Pilot commentary indicated that the Enhanced Flight Visual System (EFVS) – forward looking infrared (FLIR) on a HUD - provided suitable visual references to complete the flare and landing. Future research should examine the effects of potentially eliminating the natural vision/visual segment requirement of FAR §91.175 in other than Category II or III operations while conducting low visibility approach and landing with an EFVS.

Rare Events

The ability of the flight crew to handle a runway incursion was neither impacted nor significantly aided by the display concepts tested. Although the increase in near-domain symbology information (runway outline) did not degrade pilot response to the Fire Truck runway incursion event, there was also not an observed enhancement in incursion detection as hypothesized for the FLIR. The display concepts and scenarios tested in this experiment – typical of current and future PF HUD and pilot-not-flying auxiliary displays - did not show adequate incursion detection functionality. Numerous factors contributed to this result including

the location and size of the incursion vehicle which somewhat blended into the runway markings and was occluded by flight display symbology. As a consequence, only one of the runway incursion scenarios was detected using the cockpit displays, which included EV. These results do not necessarily suggest that the EV has no value in runway incursion detection. However, the imaging sensor alone does not provide sufficient capability to significantly and reliably prevent occurrence of these events. Therefore, sensor and display design must be tailored to this function and corresponding crew procedures and interfaces developed to support runway incursion detection.

In addition to runway incursion detection, another rare event scenario evaluated the ability of the flight crew to perform their required crew procedures and handle a substantial navigation solution error. The lateral navigation errors were verbally acknowledged a significant percentage of time, and had minimal, if any, impact on the flight crews ability to make the necessary adjustments to land safely and accurately on the runway. These results lend convincing evidence that the potentially compelling display of pathway information (in the form of a runway outline in this test) does not adversely capture attention nor induce pilots to follow erroneous display information in the presence of real-world visual information or other display cross-checks.

The emerging NextGen operational concepts will require revolutionary approaches to help meet the many new challenges of the future air transportation system. Synthetic and enhanced vision systems offer promising enabling technologies to proactively overcome aircraft safety barriers that would otherwise constrain the full realization of the next generation air transportation system. This research should lead toward the development of new operating concepts – such as 4D navigation and self-separation (see Joint Planning and Development

Office, 2004) – as well as all-weather operations capabilities, approaching that which might create an equivalent visual operations capability, yet without necessarily requiring the magnitude of airport or aircraft infrastructure associated with today's instrument flight operations.

References

- Arthur, J. J., III, Kramer, L. J., & Bailey, R. E. (2005). Flight test comparison between enhanced vision (FLIR) and synthetic vision systems. *Proceedings of SPIE, Enhanced and Synthetic Vision 2005, Volume 5802*, 25-36.
- Arthur, J. J., III, Prinzel, L. J., Kramer, L. J., Bailey, R. E., and Parrish, R. V. (2003) CFIT prevention using synthetic vision. *Proceedings of SPIE, Enhanced and Synthetic Vision 2003, Volume 5081*, 146-157.
- Bailey, R. E., Kramer, L. J., & Prinzel, L. J., III. (2006). Crew and display concepts evaluation for synthetic/enhanced vision systems. *Proceedings of SPIE, Enhanced and Synthetic Vision Conference 2006, Volume 6226*, 62260G.1-62260G.18.
- Bailey, R. E., Kramer, L. J., & Prinzel, L., III. (2007). Fusion of synthetic and enhanced vision for all-weather commercial aviation operations (NATO RTO-HFM-141). *NATO Human Factors and Medicine Symposium on Human Factors and Medical Aspects of Day/Night All Weather Operations: Current Issues and Future Challenges*, 11-1 through 11-18.
- Boff, K. R. & Lincoln, J. E. (Eds.). (1988). *Engineering data compendium: human perception and performance*. Wright Patterson AFB, OH: Armstrong Aerospace Medical Research Laboratory.
- Connor, G. L. & Mages, J. G. (1993). The research and development of enhanced vision systems. *Proceedings "Looking Ahead", Symposium on Head Up Display, Enhanced Vision and Virtual Reality*, October 25-26, Amsterdam, The Netherlands.
- Foyle, D. C. & Hooey, B. L. (2003). Improving evaluation and system design through the use of off-nominal testing: a methodology for scenario development. *Proceedings of the 12th International Symposium on Aviation Psychology*, pp. 397-402.

Joint Planning and Development Office. (2004). *Next generation air transportation system integrated plan*. Washington, DC: Author.

Kramer, L. J., Arthur, J. J., III, Bailey, R. E., & Prinzel, L. J., III. (2005). Flight testing an integrated synthetic vision system. *Proceedings of SPIE, Enhanced and Synthetic Vision 2005, Volume 5802*, 1-12.

Kramer, L.J., Prinzel III, L.J., Arthur III, J.J., & Bailey, R.E. (2005). *Advanced pathway guidance evaluations on a synthetic vision head-up display* (NASA TP-2005-213782). Washington, DC: NASA.

Larimer, J., Pavel, M., Ahumada, A. & Sweet, B. (1992). Engineering a visual system for seeing through fog. *SAE 22nd International Conference on Environmental Systems, Volume 921130*, 428-432.

McKay, D., Guirguis, M., Zhang, R. & Newman, R. L. (2002). Evaluation of EVS for approach hazard detection (NATO RTO-MP-107). *The RTO Sensors and Electronics Technology Panel (SET) Workshop*, NATO Research and Technology Organization.

National Aeronautics and Space Administration. (n.d.). *Aviation safety program / integrated intelligent flight deck technical plan summary*. Retrieved October 3, 2007, from http://www.aeronautics.nasa.gov/nra_pdf/iifd_tech_plan_c1.pdf

Parrish, R. V, Busquets, A. M., Williams, S. P., & Nold, D. E. (2003). *Evaluation of alternate concepts for synthetic vision flight displays with weather-penetrating sensor image inserts during simulated landing approaches*(NASA TP-2003-212643). Washington, DC: NASA.

Schiefele, J., Howland, D., Maris, J., Pschierer, C., Wipplinger, P., & Meuter, M.(2005). Human factors flight trial analysis for 3D SVS: Part II. *Proceedings of SPIE, Enhanced and Synthetic Vision 2005, Volume 5802*, 195-206.

Schnell, T., Theunissen, E., & Rademaker, R. (2005). Human factors test & evaluation of an integrated synthetic vision and sensor-based flight display system for commercial and military applications. *Proceedings of the NATO/RTO HFM-125 Toward Recommended Methods for Testing and Evaluation of EV and E/SV-Based Visionic Devices Workshop*, Williamsburg, VA.